

WAVE ACTIVITY IN LAKE ERIE NEAR ASHTABULA, OHIO¹

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ABSTRACT. A study of the hydraulic regime of Lake Erie near Ashtabula, Ohio, was conducted from June 1975 to September 1976. The objective of the study was to determine the deposition and fate of dredged material disposed in Lake Erie. One of the aspects of this study involved the observation of wave activity in this area, to determine the general wave climate and the potential for wave energy to resuspend and transport sediments.

A pressure sensitive wave gauge was placed at 17 m depth approximately 6 km offshore north of Ashtabula Harbor. Wave measurements were taken every 4 h. Visual wave observations were also obtained during the study period from 2 locations east and west of Ashtabula Harbor to document wave activity.

The average wave period measured was about 5.5 sec. Most of the waves were less than 1 m high but during a storm the wave height frequently reached 2 m. Although the generation time required for development of wave fields varied, the majority of waves measured on Lake Erie gradually increased during a storm and reached maximum values after 20 h at or slightly after the peak of the storm. The majority of the wave orbital velocities was less than 1 cm/sec. near the bottom at the study site, but under storm conditions the value increased to over 10 cm/sec. The greatest percentage of waves approached the shore from the northwest.

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INTRODUCTION

This project was part of a larger study which investigated the hydraulic regime and the physical nature of bottom sedimentation in Lake Erie near Ashtabula, Ohio. The study was an integral part of a Dredged Materials Research Program (DMRP) conducted by the U. S. Army Corps of Engineers Waterways Experiment Station (WES) in Vicksburg, Mississippi. The study was conducted in relation to the aquatic disposal field investigations at the Ashtabula, Ohio, dredged material disposal site.

As part of the study a pressure sensor for measuring and recording wave height was located near a current meter mooring at

location PC 1a in 17 m of water. Also, to document wave activity, visual wave observations were taken from 2 locations, one east and one west of Ashtabula as shown in an earlier paper (Alther 1981). More precisely, the western station lies west of the western aqueduct, and the eastern station about 1 km west of the eastern aqueduct. The station PC 1a was located 200 m off the southwest corner of the disposal area, and the old station PC 1b was located some 2 km north-west-north of the western visual wave observation station. The study commenced in June 1975 and ended in September 1976.

In mid-November the location of the wave sensor was moved to approximately 500 m offshore north of the west wave observation point in approximately 6 m of water, because location PC 1a was consid-

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ered too deep. It was feared, however, that the data from the new location would not be representative of waves at the study site because 1) refraction might occur due to lake bottom topography, and 2) that the Ashtabula Harbor would deflect waves coming from the northeast. For this reason, the wave sensor was moved back to PC 1a in 1976. The instrument was retrieved from the water in December and redeployed in March 1976 as winter servicing was not possible. Even though this location (PC 1a) was too deep to accurately measure small, short period waves, interesting results were obtained over the 2 sampling periods. These results and their interpretations are reported in this article.

METHODS AND MATERIALS

A Bass Engineering Model WG/100M self-contained wave measuring and recording system was installed in approximately 17 m of water near PC 1a. The instrument senses pressure fluctuations with a Bourdon tube pressure transducer whose signal is transformed with an optical lever system to produce a variable voltage output. The operation of the optical lever system is described in detail by Bass and Byrnes (1974). The system determines water surface variations with a precision of ± 0.6 cm and a resolution of ± 0.3 cm. The timing is controlled by a crystal clock which has an accuracy of $\pm 0.01\%$. The wave field was sampled every 4 h for a 10-min interval during which time measurements were taken every 0.5 sec. In March 1976, the sampling rate was changed to 1.0 sec to increase the recording capacity of the instrument. The data were recorded on a magnetic cassette which was later decoded. The results were stored on magnetic tape.

The data were edited to remove all bad characters from the data sets and to check for the proper timing sequence that precedes each data set. The resulting data sets were detrended and the mean was subtracted, which left only the pressure fluctuations about a zero mean. The residual pressure readings were plotted and examined to remove any outlying points. All erroneous points were replaced by a linear interpolation of the 2 adjacent points. The "clean" data sets obtained after the editing process were used for subsequent analysis.

We used the "consecutive zero-up-crossing method" to analyze the wave data. This method defined the point where the water level signal changed from negative to positive at the beginning of the wave and the next zero-up-crossing at the end of the wave. The wave height for each wave was determined by calculating the difference between the maximum and minimum water level values between consecutive zero-up-crossings. The wave

period was the time interval between up-crossings. The entire data set for each 10-min recording interval was analyzed in this manner and typically 100 waves were tabulated. These waves were sorted according to wave height, and the highest $\frac{1}{3}$ were averaged to determine the significant wave height for that recording interval. The periods from these waves were averaged to determine the wave period. The maximum wave measured during each interval was also tabulated.

The wave gauge was located so deep that the pressure signals resulting from small short period waves were extremely weak. Consequently the results were further edited to eliminate values that were below the detection limits of the instrument at that depth. These weak signals produced such small fluctuations in the measured water levels that the zero-up-crossing method was not effective in locating the beginning and ending of the waves. As a result, very small long-period waves were frequently recorded. To eliminate this problem an arbitrary maximum period of 10 sec was assigned. Small waves with periods greater than 10 sec were considered erroneous and deleted from the record. The decision may have deleted a few good data points, but waves with periods greater than 10 sec are extremely uncommon on the Great Lakes (Liu and Kessenich 1975), and when they do exist it is only under severe storm conditions. After these bad points were deleted, each recording interval was visually examined and records with less than 20 remaining good waves values were considered untrustworthy and eliminated. Significant wave heights and wave periods were calculated for the remaining data sets as described above.

Since the wave gauge was located on the bottom and the pressure signals from the water level fluctuations decrease with depth in the water column, the measured wave height values were corrected to estimate the actual wave heights at the water surface. The corrections for this attenuation of the pressure fluctuations with depth were made as described by Kim and Simons (1974). The wave height at the surface H is related to the measured wave at the bottom H_b by the equation:

$$H = \frac{\cosh(KD)}{\cosh K(D - Z)} H_b \quad (1)$$

Where Z is the depth of the sensor, D is the total water depth and K is the wave number. The wave number was determined implicitly from the dispersion equation:

$$w^2 = gK \tanh(KD) \quad (2)$$

Where g is the acceleration due to gravity and W is the frequency which is equal to $2\pi/\text{period}$. The procedure followed was to first determine H_b from the zero-up-crossing method and then compute H from equation 1. Equation 2 was used to calculate

K , which used the wave period determined from the zero-up-crossing routine.

This method of correcting for attenuation by using a single wave period can result in underestimating the actual wave height (Harris 1972). However, the method provided reasonable results and precluded using power spectra techniques which would have been difficult because of the weak pressure signals resulting from the deep location of the wave sensor. An estimation of the maximum value of the orbital velocity of the wave field at the bottom was then made by using H_b according to:

$$\text{Orbital Velocity (O. V.)} = \pi H_b / \text{Period} \quad (3).$$

A similar method for computing orbital velocities is described in detail by Kinsman (1965).

The final results of the wave record analysis were a tabulation of significant and maximum wave heights and average wave period for every 4 h while the instrument was in operation. The estimations of the orbital velocities near the bottom were also tabulated for each 4-h interval as was the wind speed during the time of the observation (Danek et al. 1977).

In addition to the wave recorder data, wave direction data were collected twice each day by observers at locations west and east of Ashtabula Harbor. Each observer was provided with a Lensatic compass to sight perpendicular and parallel to the wave crests as far off-shore as possible and to determine the direction from which waves were propagating. Time of day and occasional wave height estimates were also recorded. Histograms of wave direction by compass sector were developed from these data.

RESULTS AND DISCUSSION

WAVE GAUGE OBSERVATIONS. The wave gauge successfully recorded water level fluctuations for 10 periods averaging about 21 days each with 6 sampling intervals of 10 min duration per day. The wave periods were generally between 4.5 and 6.5 sec which is 1 or 2 sec higher than the values obtained by Liu and Kessenich (1975) on Lake Ontario.

The recorded wave periods were higher than expected because the shorter period waves were below the detection limits of the pressure sensor located in such deep water. Short period waves attenuate more rapidly with depth than longer period waves so the results are biased in favor of higher periods. Tabulated results were computed from the detectable pressure fluctuations in 17 m of water at the disposal site which excludes the detection of waves with periods shorter than 3.5 sec. Therefore care must be taken when examining the wave results because they are not an exact description of the actual water surface fluctuations, but rather an estimate from measured pressure fluctuations. An example of wave data obtained is shown in table 1.

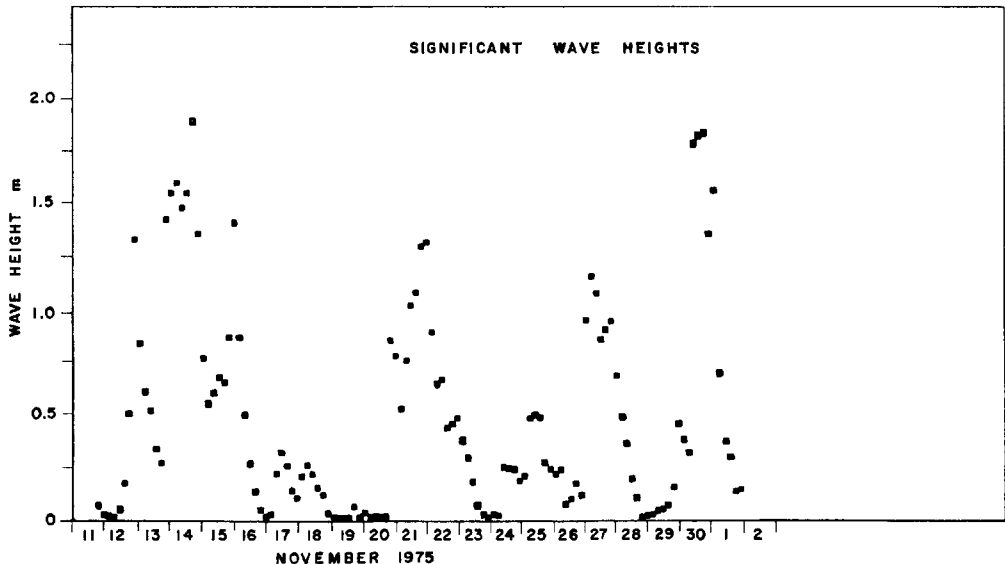


FIGURE 1. Significant wave heights for 11 November to 2 December, 1975.

TABLE 1
Wave data for 11 November to 2 December, 1975.

Date	Time Hr	H _{1/3} m	Period Sec	Hmax m	O.V. cm/sec	Wind m/sec	Date	Time Hr	H _{1/3} m	Period Sec	Hmax m	O.V. cm/sec	Wind m/sec
11 Nov	16	0.07	4.3	0.12	0.0	2.2	20 Nov	00	0.02	4.8	0.03	0.0	3.1
	20	0.02	4.7	0.03	0.0	2.6		04	0.04	4.4	0.06	0.0	3.5
12 Nov	00	0.02	5.3	0.03	0.0	2.2		08	0.01	5.9	0.02	0.1	4.4
	04	0.01	7.5	0.01	0.1	4.4		12	0.01	6.6	0.02	0.1	5.3
	08	0.05	4.9	0.07	0.1	3.5		16	0.02	6.2	0.02	0.1	6.2
	12	0.18	4.7	0.30	0.3	2.6		20	0.01	6.9	0.02	0.1	5.3
	16	0.52	5.2	0.73	1.7	5.3	21 Nov	00	0.88	4.8	1.23	1.8	8.0
	20	1.37	6.0	1.79	8.3	9.8		04	0.80	6.4	1.24	6.0	3.1
13 Nov	00	0.87	6.1	1.18	5.7	5.3		08	0.54	5.7	0.80	2.6	5.3
	04	0.62	5.6	0.97	2.9	4.4		12	0.78	6.1	1.23	5.1	6.2
	08	0.54	5.8	0.83	2.8	3.1		16	1.05	6.5	1.46	8.1	5.3
	12	0.35	5.2	0.53	1.2	3.1		20	1.11	6.7	1.53	9.3	4.4
	16	0.28	4.7	0.56	0.4	4.0	22 Nov	00	1.33	6.0	1.84	8.2	9.8
	20	1.46	6.1	1.79	9.4	9.8		04	1.35	5.7	1.84	6.9	8.0
14 Nov	00	1.59	6.3	1.99	11.1	11.1		08	0.92	5.6	1.73	4.2	4.9
	04	1.64	6.2	2.11	11.2	12.5		12	0.66	4.7	1.01	1.2	6.2
	08	1.52	6.0	2.13	9.4	11.1		16	0.68	4.4	1.05	0.7	4.9
	12	1.59	6.1	2.30	10.0	9.8		20	0.45	4.8	0.78	0.9	4.4
	16	1.94	6.2	2.36	12.9	9.3	23 Nov	00	0.47	4.8	0.62	1.0	2.6
	20	1.39	6.2	2.18	9.2	8.0		04	0.50	4.9	0.90	1.2	3.5
15 Nov	00	0.79	5.0	1.31	2.1	6.2		08	0.38	4.5	0.65	0.4	3.1
	04	0.56	5.0	0.73	1.4	4.0		12	0.31	4.1	0.55	0.1	5.8
	08	0.62	5.4	0.98	2.5	5.3		16	0.19	3.9	0.24	0.0	2.2
	12	0.69	6.1	1.09	4.3	6.2		20	0.06	4.0	0.11	0.0	2.6
	16	0.67	6.0	0.96	4.0	4.9	24 Nov	00	0.03	4.6	0.04	0.0	2.6
	20	0.89	6.5	1.56	6.8	4.0		04	0.02	4.8	0.02	0.0	2.6
16 Nov	00	1.44	6.6	1.68	11.6	5.8		08	0.02	4.8	0.04	0.0	2.2
	04	0.89	5.9	1.46	5.2	4.9		12	0.02	4.8	0.04	0.0	2.6
	08	0.51	5.3	0.77	1.9	1.7		16	0.26	3.7	0.40	0.0	4.4
	12	0.28	4.5	0.41	0.3	2.6		20	0.25	4.2	0.60	0.2	4.9
	16	0.14	4.3	0.25	0.1	0.8	25 Nov	00	0.25	4.4	0.37	0.2	2.2
	20	0.05	4.5	0.08	0.0	3.1		04	0.19	4.6	0.27	0.2	2.2
17 Nov	00	0.02	5.3	0.02	0.0	3.5		08	0.21	4.6	0.41	0.3	4.0
	04	0.03	5.3	0.05	0.1	3.5		12	0.50	5.3	0.72	1.9	4.4
	08	0.23	4.6	0.38	0.3	4.0		16	0.51	5.4	0.78	2.1	4.4
	12	0.33	4.5	0.42	0.4	4.9		20	0.50	5.6	0.84	2.3	3.1
	16	0.27	4.4	0.38	0.2	2.2	26 Nov	00	0.28	5.0	0.39	0.7	4.0
	20	0.14	4.2	0.27	0.1	3.5		04	0.25	4.8	0.55	0.5	3.1
18 Nov	00	0.11	4.0	0.17	0.0	3.1		08	0.23	4.7	0.36	0.4	4.4
	04	0.22	3.8	1.57	0.0	3.1		12	0.25	4.4	0.38	0.2	2.6
	08	0.27	4.0	0.43	0.1	3.1		16	0.08	4.2	0.11	0.0	3.1
	12	0.23	3.9	0.35	0.0	4.4		20	0.10	4.0	0.16	0.0	3.5
	16	0.16	4.0	0.26	0.0	1.3	27 Nov	00	0.18	4.7	0.34	0.3	5.8
	20	0.12	3.9	0.20	0.0	2.6		04	0.12	5.6	0.17	0.5	7.1
19 Nov	00	0.04	4.1	0.05	0.0	3.1		08	0.97	5.8	1.49	5.3	7.6
	04	0.02	4.4	0.03	0.0	3.1		12	1.19	7.2	1.60	11.4	6.7
	08	0.01	4.9	0.01	0.0	3.1		16	1.10	6.8	1.54	9.3	5.3
	12	0.01	6.0	0.02	0.0	2.6		20	0.88	5.9	1.32	4.9	5.8
	16	0.02	4.9	0.05	0.0	1.3	28 Nov	00	0.93	5.8	1.32	4.8	5.8
	20	0.07	4.5	0.09	0.0	2.6		04	0.97	6.0	1.38	6.0	5.3

The majority of the recorded waves were less than 1 m which is typical for waves on the Great Lakes (Liu and Kessenich 1975). During storm conditions the significant wave heights frequently reached nearly 2 m with maximum waves greater than 2.5 m. The largest waves were measured during November 1975 (figure 1), which was a direct result of the higher wind speeds during that month. There were 2 storms in November, one on the 14th and one on the 30th. In both cases the hourly wind speed averaged greater than 13 m/sec and waves of nearly 2 m were generated. Several other storms also produced large waves (e. g. on 24 September 1975, 19 May 1976 and 7 June 1976) and in most cases a gradual build-up of the wave field was observed. Waves typically increased for about 20 hours before they peaked either at or slightly after the peak of the storm. Then they slowly subsided with the passing of the storm.

The oscillatory water particle motions of the waves usually diminished to less than

1 cm/sec at the bottom. This value increased considerably under storm conditions. During the storm of 14 November 1975, the magnitude of the velocity at the bottom averaged over 10 cm/sec for a 24-h period. On 1 December 1975, the speed reached 20 cm/sec for a short time. These motions were qualitatively confirmed by a diver who could easily feel the oscillatory motions at the bottom while servicing instruments during a period of 1.0 to 1.5 m waves.

These high speeds did not occur very often, but they could be important in re-suspending sediments. The speeds were generally not great enough alone to re-suspend the sediments, but when superimposed with the ambient currents they could easily add enough energy for sediment resuspension. Assuming a typical erosion velocity of 20 cm/sec, then a 10-cm/sec current speed in conjunction with a 10-cm/sec component from the wave field would provide sufficient energy for sediment resuspension. However, dur-

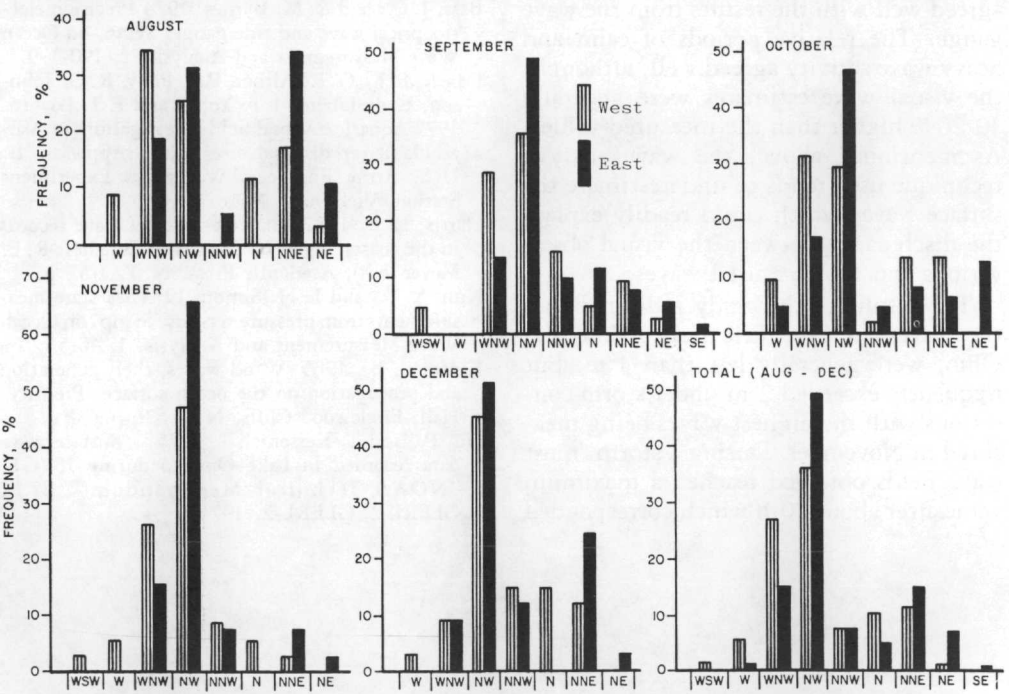


FIGURE 2. Histograms of wave directions observed from shore from August to December, 1975.

ing November, 8% of the measurements were greater than 10 cm/sec, which indicates that November might have been the most active month for sediment erosion.

VISUAL WAVE OBSERVATIONS. Monthly histograms of observed wave directions for 1975 and 1976 are presented in figure 2. Visual observations were made both west and east of the harbor with no obvious differences. The majority of the waves approached from the northwest and the west-northwest sectors, due mainly to the westerly winds producing waves that were refracted as they approached the shore. The refraction caused the eastward traveling waves to bend shoreward which made them appear to be coming out of the northwest. Several of the monthly histograms showed a secondary concentration of waves out of the north-northeast. These waves were produced by winds out of the northeast that were also refracted as they entered shallow water.

Occasional wave height estimates were taken by the wave observers. These values agreed well with the results from the wave gauge. The relative periods of calm and heavy wave activity agreed well, although, the visual wave estimates were generally 10-20% higher than the measured values. As mentioned above, the wave analysis technique used tends to underestimate the surface waves which could readily explain the discrepancy between the visual observations and the measured waves.

The results of the study indicated that the waves on Lake Erie near Ashtabula, Ohio, were generally less than 1 m, but frequently exceeded 2 m under storm conditions with the highest waves being measured in November. During a storm, most wave fields observed reached a maximum value after about 20 h which corresponded

to the peak of the storm. Wave energy diminished rapidly with depth, but under storm conditions sufficient energy reached the bottom even in 17 m of water to aid in sediment resuspension.

The study also showed that waves can be measured with a pressure sensor in water as deep as 17 m. However, this is near the feasible limit as pressure signals from small, short-period waves attenuate rapidly with depth. At this depth waves with periods less than 3.5 sec generally could not be detected. Also, for better resolution, the wave recording interval should be 0.25 sec or less.

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